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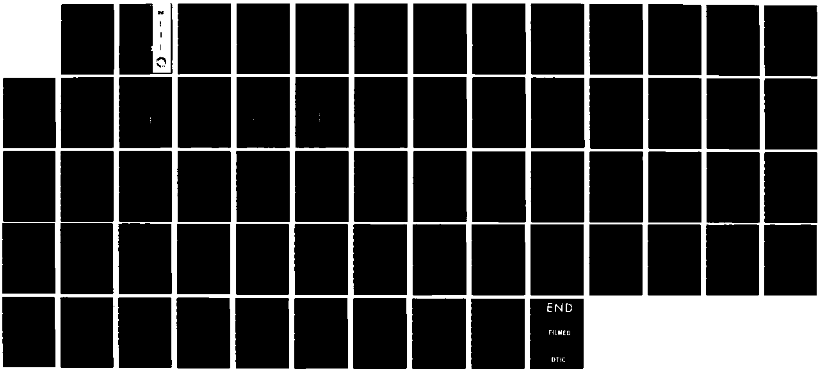

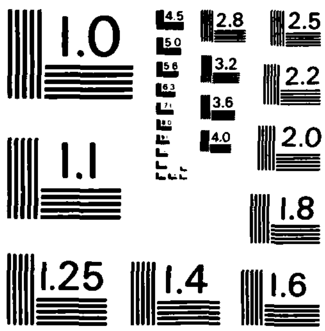

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Extended area exit pupil viewer

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August 1985

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Prepared for
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report describes the process of designing and building a prototype Extended Area Exit Pupil viewer. This system will enable comfortable viewing of a projected stereo image. It works by enlarging the microscope's exit pupil, thus allowing increased head movement while maintaining stereo separation of the images.

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PREFACE

This document describes work performed under contract DACA76-83-C-0008 for the U.S. Army Engineer Topographic Laboratories, Fort Belvoir, Virginia, by EIKONIX Corporation, Bedford, Massachusetts. The Contracting Officer's Technical Representative was Mr. Maurits Roos.

EIKONIX

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1.0 INTRODUCTION

This is the Final Report on the Extended Area Exit Pupil (EAEP) Viewer Program. During this two year program extending from September 1, 1983 to August 30, 1985, EIKONIX Corporation has designed and built a prototype EAEP viewer; later named the EIKONIX HSD-500 (Heads-Up Stereo Display). The EAEP viewer enlarges the exit pupils from a stereomicroscope and presents the image on a screen, thereby allowing increased head movement while maintaining stereo separation of the image. The viewer provides relief from the neck, back, and eye strain normally associated with stereo viewing. The objective of the EAEP viewer program was to supply a prototype viewer that would allow comfortable viewing of a projected stereo image.

All of the design objectives for the viewer have been successfully demonstrated in the prototype viewer. Areas where the instrument fell short of design goals includes allowable operator head movement and image brightness. In each of these cases, the cause of the problem has been identified and solutions are available. Although generally adequate, further improvement to provide greater image illumination would extend the use of the instrument on denser imagery.

The HSD-500 viewer has been supplied as an attachment to a Bausch & Lomb Zoom-500 stereomicroscope and Richards HFO-500 light table. The Richards light table has been modified by the addition of two high-intensity light sources. Modification to the light sources was necessary in order to meet the increased illumination requirements of the EAEP viewer. The viewer provides comfortable viewing of a usably bright projected stereo image. Excellent, flicker-free images are obtained with resolution nearly equal to that of the Zoom-500 alone. All the features of the Zoom-500 stereomicroscope remain functional, including the standard measurement reticle with angle readout

which is incorporated into the HSD-500. The HSD-500 is designed to allow easy transition from heads-up viewing to normal Zoom-500 stereomicroscope viewing.

Previous EAEP viewers typically have incorporated a spinning lenticular screen and associated projection optics and are recognized as having many disadvantages (see Figure 1.0-1). Because the screen used for enlarging the exit pupils is coarse in structure, the structure must be blurred by rapidly rotating the screen. This rotational motion typically produces vibration, degradates resolution, and induces flicker. In addition, a concentric pattern is generated by the revolution of the screen as the sharp boundaries of the lenticules trace out arcs about the axis of rotation. This pattern persists at all rotational velocities.

The EIKONIX EAEP viewer has been designed to eliminate these problems. The design does not use any rotational or mechanically moving parts. Exit pupil expansion is accomplished by two liquid crystal diffusers. This passive optical approach incorporates no rapidly moving parts that blur or vibrate the image.

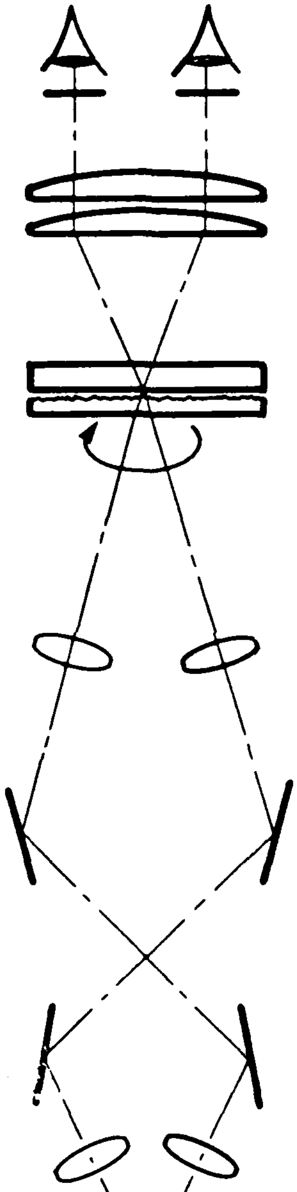


Figure 1.0-1 Spinning Screen EAEP System

Figure 3.4-1 shows the optical system of Figure 3.3-1 folded into the EAEP system package. The image beam coming from the microscope is reflected downwards by the right angle prisms into the first set of relay lenses. Beam crossover is accomplished between the first relay lenses and the LC diffuser using roof prisms. The crossover must be done carefully to prevent image rotation and also to preserve left-right orientation. Left-right orientation is preserved by providing the proper number of reflections through the optical system. To accomplish this, a double reflection is required at one of the fold points. The roof prisms are used to provide this extra reflection. To prevent rotation between the right and left images, the roof-prisms and first set of mirrors are positioned at exactly 90 degree angles to each other. In this configuration, the right and left images are rotated exactly the same amount. From the first set of mirrors, the light travels upwards through the LC diffuser and the large aperture relay lenses. The light is reflected off a 7 inch x 7 inch plane mirror at the top of the EAEP package. This mirror directs the beam towards the field mirror that projects the exit pupils through the window in the front of the EAEP system.

The optical path illustrated in Figure 3.4-1 contains six reflections and two image relay lenses. The five reflective elements produce the six reflections because one element is a roof prism which reflects doubly. This configuration, since it has an even number of reflections and an even number of image relay lenses, produces an image which is correctly oriented with respect to the spatial correspondence of objects in the image. For example, an object such as a written word will show the correct relationship and orientation between the letters of the word. This performance is achieved in any position of rotation of the image.

The path by which the image is reflected along its circuit causes the EAEP image to become rotated 180 degrees from

In order to increase the light throughput and to reduce the amount of flare light, all of the lens and prism surfaces have been anti-reflection coated.

3.4 Optical System Geometry

A primary objective in the design of the optical system was to keep the mechanical package as compact as possible, while maintaining correct image orientation and operator comfort.

The instrument's package must be kept small to allow the operator access to the light table and Zoom-500 controls. In addition, it must swing easily out of the way to allow normal eyepiece viewing. The situation is complicated by the beam crossover which must be accomplished before the diffusing screen. Rotation between the right and left images is not allowed, since when in the mono and superimposition modes, the images would then be misaligned. Correct right reading orientation must also be preserved.

The complexity of the EAEP optical system creates a large matrix of possible geometries. Initially, many possible designs were considered. Some differed radically from the final design configuration, while others were very similar. One design that warranted serious consideration involved crossing the beams within the Zoom-500. The Zoom-500 uses a prism as a switch between mono and stereo viewing. The prism has a 50% beam-splitter portion for mono viewing and a totally reflective portion for stereo viewing. If the prism were removed from the beam path altogether, the beams would cross inside the microscope. This would have simplified the EAEP optical system design by eliminating the need to perform beam crossing within the EAEP. However, it would have meant performing a modification to the Zoom-500 itself. This modification may have caused misalignment of the Zoom-500 optics requiring time-consuming realignment. The "prism switch" method also presented negligible savings in cost and complexity and was thus discarded.

'll the aperture of the 57mm lens. The light distribution across the aperture will correspond to the image brightness seen by the viewer as he moves his eye across the exit pupil. At this diffuse image location is another field lens comprised of two 100mm plano-convex lenses placed on either side of the LC diffuser. These lenses serve to efficiently direct the light from the diffuse image into the aperture of the second relay lens, thus greatly increasing the image brightness. They are also offset slightly in order to direct the light inwards to the center of the large field mirror.

The second relay lens projects the diffuse image onto the field mirror at 7X magnification. In turn, the field mirror forms a 1:1 image of the relay lens aperture, 18 inches in front of the mirror. The image of the aperture of the second relay lens becomes the exit pupil of the system and when placed within its circumference, the eye will see the real image that lies in the plane of the field mirror. Thus, the clear aperture of the second relay lens controls the size of the expanded exit pupil. The 57mm f/1.2 Hexanon lenses were chosen specifically for their large, 44mm diameter, clear aperture. The center-to-center separation of the lenses was chosen to be 62mm. This distance represents the average interpupillary distance as reported in the Photointerpretation Instrumentation Handbook.

The original specification called for an exit pupil diameter of 50mm. For several reasons this requirement was changed to 38mm by a 1985 contract modification. There are no commercially available lenses with clear apertures large enough to provide 50mm diameter exit pupils. The 57mm Hexanon lens (44mm diameter pupils), available as a stock item, was much more cost effective than designing and fabricating a custom lens. Also, the center-to-center spacing of the lenses was set at 62mm for ergonomic reasons. Lenses with a 50mm clear aperture, and a larger front element, cannot be mounted this close together.

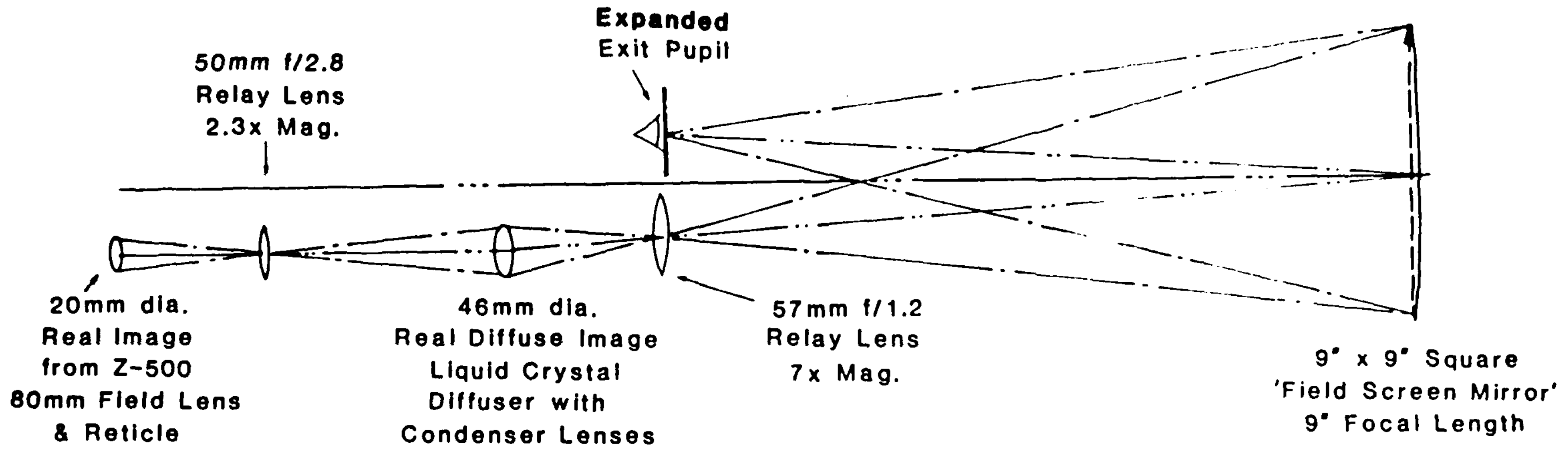


Figure 3.3-1 Unfolded System, Optical Schematic

special attention be paid to using an efficient high-intensity light source.

3.3 Optical System

The optical schematic in Figure 3.3-1 shows the unfolded optical system. This section describes the optical system design and the functions performed by the various components. Subsequent sections describe the components themselves and the folded optical path.

Within the eyepiece-holder tubes lies the real image from the Zoom-500. With 1X objectives this image can be zoomed from 0.6X to 3.3X magnification. The viewer optical system begins with an 80mm field lens at this internal image location. The field lens lies at a real image location and contributes no magnifying power. Its purpose is to restrict the cone angle of the image forming light, thus reducing the required size of lenses further down the optical path. Also at this image location lies the measurement reticle. Since the measurement is performed at this image plane, the only distortion present is that of the Zoom-500 optical system; on the order of 1%. The distortion caused by the viewer optics may be perceptible to the operator, but will not effect the measurement accuracy. The measurement reticle can be rotated and used in either the right or left eye.

An Apo-Rodogon 50mm f/2.8 enlarging lens relays the internal microscope image to the liquid-crystal diffuser at 2.3X magnification. This is the first stage of the two stage magnification performed by the EAEP viewer. The light that forms the real image at the LC diffuser is scattered by the diffuser to fill the aperture of the second relay lens; a 57mm f/1.2 Hexanon lens. Proper light scattering is crucial to the success of the pupil enlargement principal. It is important that the LC diffuser provide sufficient scattering of the light to evenly

3.0 OPTICAL DESIGN

3.1 Introduction

The EAEP system optical design maintains the basic operating principals outlined in the original proposal. However, in the research and design process, significant changes and improvements were incorporated into the design. The present prototype instrument represents the culmination of a thorough design process that considered many different components and configurations. Thus, EIKONIX is confident that the design represents a refined and effective implementation of the patented pupil expansion principal.

3.2 Bausch & Lomb Zoom-500 Stereomicroscope

The pupil enlargement principal is applicable to a variety of stereo viewing systems. This particular EAEP viewer and light source has been implemented on the Bausch & Lomb Zoom-500 stereomicroscope using 1X objectives. The EAEP system has been designed to retain all of the Zoom-500 features including: zoom; image rotation; stereo, mono, and superimposition viewing; rotating measurement reticle with angle readout; and right or left eye reticle viewing. In addition, the EAEP system has been designed to be easily interchangeable between heads-up and normal stereomicroscope eyepiece viewing.

The Zoom-500, acting as the front end optical system, levies constraints on the EAEP optical performance. During previous work at EIKONIX, the Zoom-500 contrast ratio, a measurement of stray light, was found to be 20:1. In addition to this stray light limiting overall image contrast, there is uncorrected spherical aberration and astigmatism that limit image resolution. The complex optical path in the microscope also makes it inefficient in terms of light transmission. A light throughput efficiency of only 1% to 2% requires that

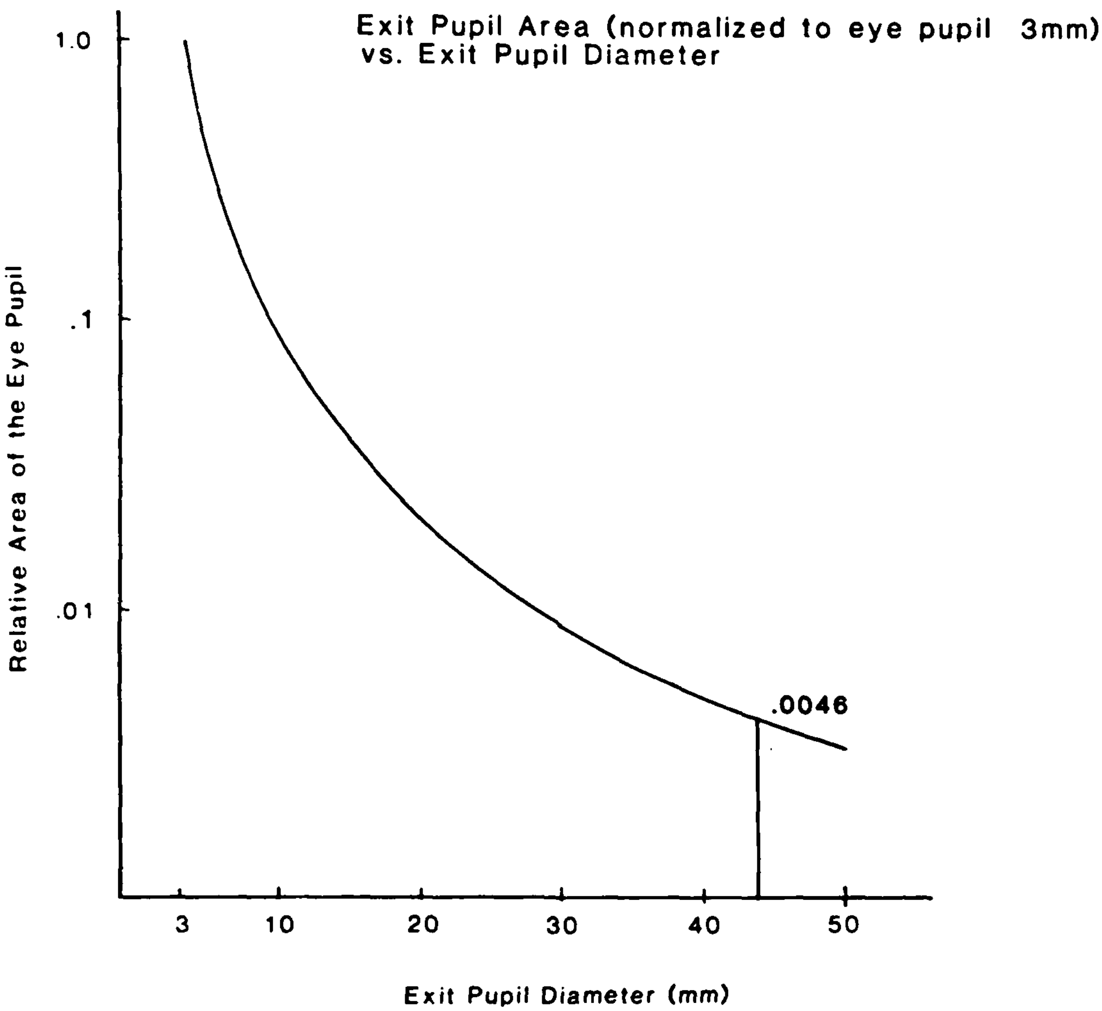


Figure 2.0-5 Relative Area of the Eye Pupil as a Function of Exit Pupil Diameter

observation space. There is no screen at the field lens, but to the observer the image appears to be projected on a screen at this plane.

With the crossover of the optical paths at the viewing screen, a reversal of the left and right images occurs. This reversal is compensated for by pre-crossing the beams prior to the diffusing screens. If this were not done, the actual film chips would have to be reversed when changing from microscope eyepiece viewing to EAEP viewing. Stereo registration would be lost and it would take time to perform re-registration.

The EAEP viewer takes light that was originally spread over the 3mm exit pupil of the normal eyepieces and expands it to cover the area of the expanded exit pupil. Because of this property, EAEP viewers inherently require greatly increased illumination. For a pupil diameter increase from 3mm to 44mm (the clear aperture of the relay lenses in the HSD-500), an increase in illumination of 215 times is required. Without considering system inefficiencies, the brightness of an image viewed with an EAEP device is equal to the brightness of the image viewed with conventional eyepieces multiplied by the square of the ratio of the eye's pupil diameter divided by the expanded exit pupil diameter (see Figure 2.0-5 and the equation below).

$$B_e = B \times \frac{D_p^2}{D_e^2}$$

B_e = EAEP brightness

B = normal eyepiece brightness

D_p = diameter of the expanded exit pupil

D_e = diameter of the standard eye pupil

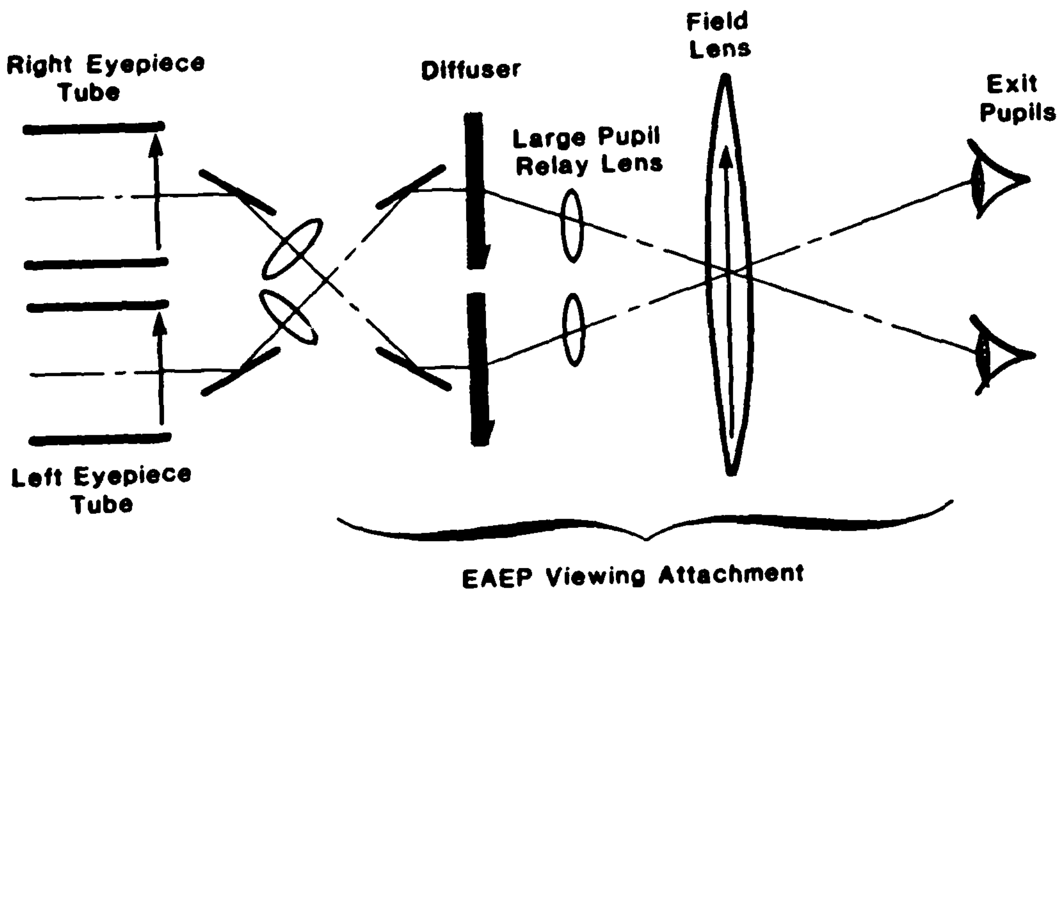


Figure 2.0-4 Optical EAEP Attachment

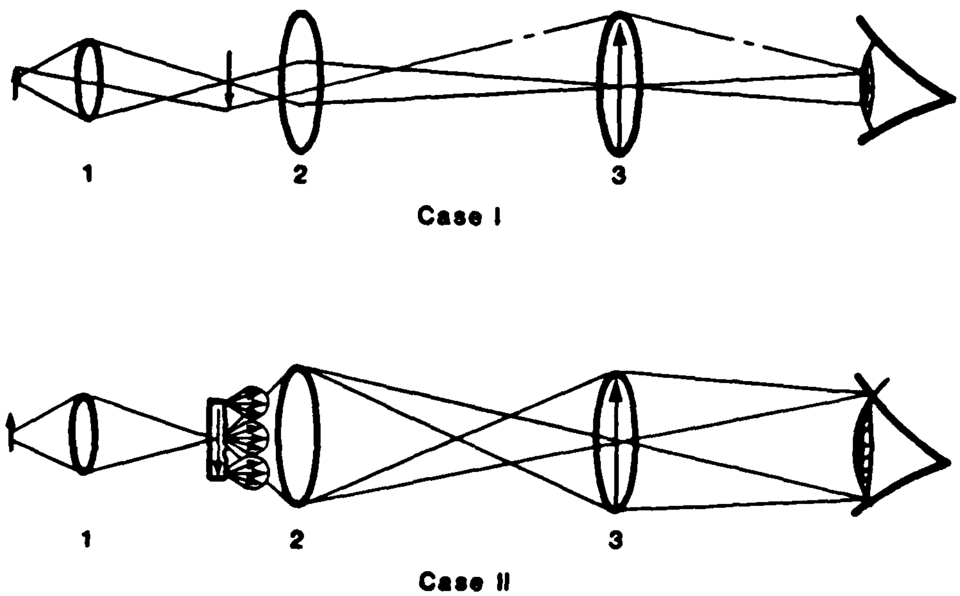


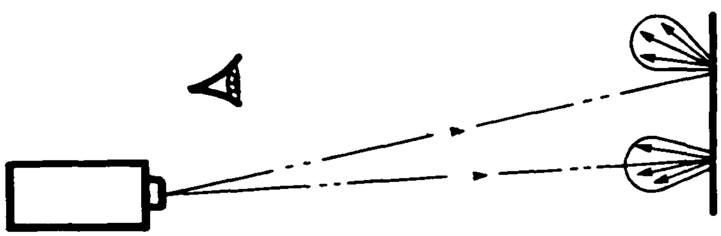
Figure 2.0-3 Exit Pupil Enlargement

and provides little or no stereo separation. The key elements of the EIKONIX EAEP system are separate left and right diffusing screens embedded in the optical system.

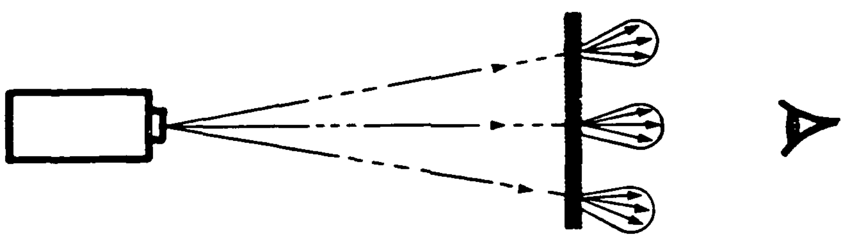
The reason that microscopes have small pupils is illustrated in Figure 2.0-3. Case I shows the optics of an erect image viewing compound microscope. Lens 1 is an objective lens which forms an inverted image. Lens 2 magnifies, inverts, and projects the image onto field lens 3. The eye is placed at the exit pupil formed by lens 3. The size of the pupil is determined by the diameter of lens 1 and the magnification of its image by lenses 2 and 3. Observe that only a small central portion of lens 2 is used and this portion corresponds to the light entering the eye. Increasing the size of lens 2, in this case, does not increase the exit pupil size.

In Case II, a diffuser has been added in the plane of the real image formed by lens 1. This diffuser causes light to scatter and fill the whole pupil of lens 2. The exit pupil formed by lens 3 is now made up of the image of the whole aperture of lens 2. The pupil has been enlarged by the diffuser, but it is still sharply defined. The brightness of the image is that of the small screen image and is much brighter than if a screen were used at the final image location.

The principle of using a small internal diffuser at an intermediate image plane has been applied to stereo viewing in the EIKONIX EAEP system (see Figure 2.0-4). The image in the eyepiece tube of a stereomicroscope is available when the eyepieces are removed. This real image is relayed by a relay lens along a crossing path to a small diffuse screen. The image on the screen is then relayed onto a large field lens. The second relay lens is a large aperture lens whose pupil is filled by the diffusing action of the screen. The field lens serves to provide both left and right images with exit pupils in the



Reflective Screen



Transmissive Screen

Figure 2.0-2 Diffuse Projection Screens

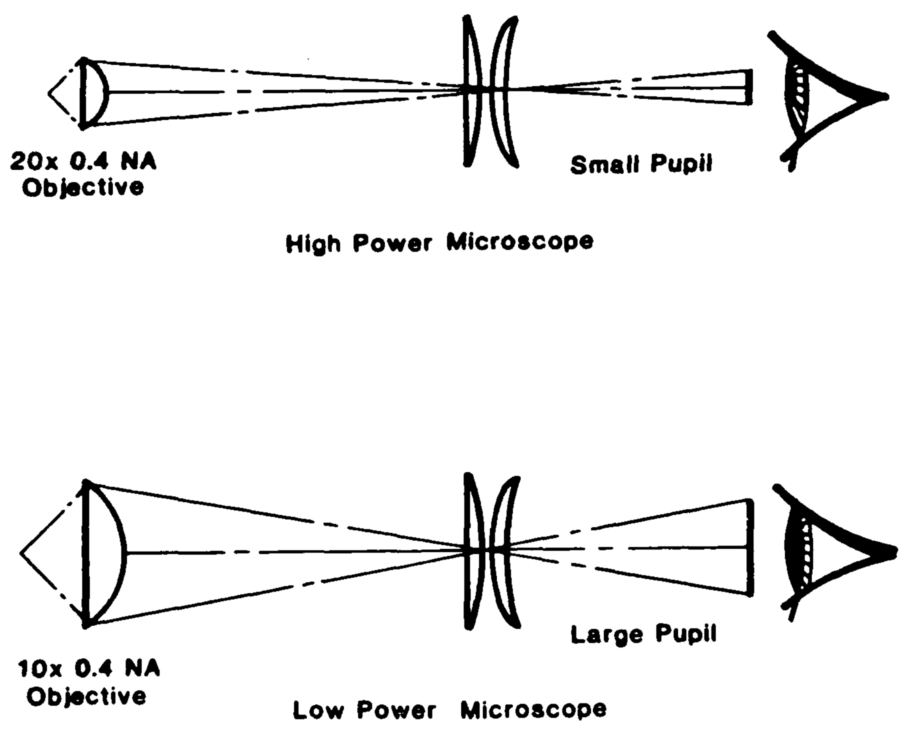


Figure 2.0-1 Pupil Size Dependence upon Magnification

2.0 OPTICAL CONSIDERATIONS and the EIKONIX EAEP APPROACH

When considering contemporary optics, the achievement of large exit pupils is possible only within the limiting physical conditions. Generally an optical system tends to produce smaller exit pupils as magnification is increased. This can be seen simply in Figure 2.0-1. With two nearly identical optical systems, it can be seen that the 20X system produces an exit pupil that is half as big as the 10X system. The only difference is in the power of the objective lenses. Because the power is proportional to the focal length, and the numerical aperture is held constant, the diameters of the objectives are inversely proportional to the power. Since the diameter of the objective controls the diameter of the exit pupil, the exit pupil size varies inversely with power.

Classical optical approaches can do nothing about the fact that exit pupil size decreases as magnification increases. However, by applying a clever alteration to the image forming process that produces pupils, they can be enlarged. The optical approach which has been developed enlarges the exit pupils without introducing artifacts to the image.

The expanded exit pupil approach used in the EAEP viewer is the subject of an EIKONIX patent. The simple optical system, without moving parts, enlarges the exit pupils by a simple diffusion step. Most projection systems use a screen surface upon which to project an image. A reflective or transmissive screen may be used. The screen diffuses the light proceeding from the image to the observer (see Figure 2.0-2), such that the exit pupils are unfocused and the entire space adjacent to the screen is considered to be the pupil. A simple diffuse screen is unsuitable for the observation of a stereo image pair because independent pupils are not produced. Also, the diffuser screen efficiency is low because the light is so widely scattered. A screen surface as a final image surface is, therefore, too dim

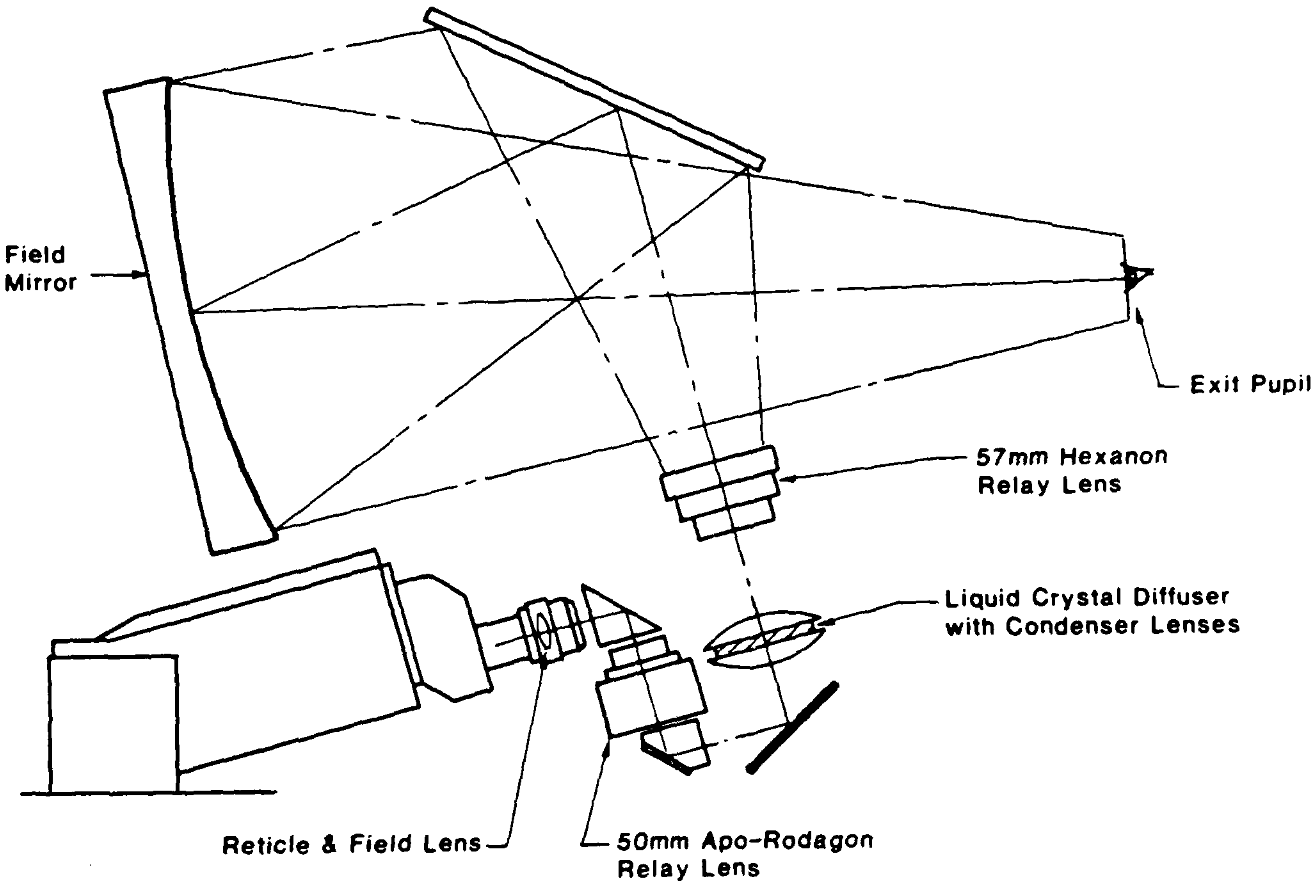


Figure 3.4-1 EAEP Viewer Folded Optical System

its orientation as viewed through the eyepieces. This configuration was chosen because it used the fewest optical surfaces for refraction and reflection of the beam, keeping the light efficiencies at a maximum, and the package size and weight to a minimum. To remove the 180 degree flip would require at least two more reflections of the beam or a third relay lens. Either of these orientation correction methods would greatly increase the packaging difficulty, cost, and complexity of the optical system. Considering the minor effort of moving the image rotators when switching between viewing modes, the 180 degree flip was allowed to remain in the final design.

3.5 Image Diffuser

Perhaps the most important design innovation for the viewer was the incorporation of a dynamic scattering liquid-crystal diffuser. During research on the breadboard lab setup, it was discovered that even special high-resolution diffusing screens were unable to provide the necessary resolution. Although some screen materials, specifically Da-Lite Screen LS-85, claim a resolution of 85 lp/mm, not more than 20 lp/mm was obtainable in practice. The 85 lp/mm specification is determined by projecting a high-quality, high-contrast image onto the screen material. In the EAEP system we are projecting low-contrast, attenuated modulation imagery, from the Zoom-500 onto the screen. The effect of the Zoom-500's flare and spherical aberration is amplified by the image diffuser. Further image degradation by the diffuser itself results in the large decrease in resolution.

A solution to this problem was found in the application of liquid crystal technology. A dynamic scattering diffuser can be made by placing a bipolar liquid-crystal (LC) material between glass plates that have a transparent conductive coating on their inside surfaces. Application of an AC voltage between the plates causes rapid motion of the bipolar liquid crystal molecules. Movement of the liquid crystal molecules causes a rapidly chang-

ing non-isotropic refractive index that scatters the incident light. The amount of scattering is proportional to the voltage driving the LC cell. Thus, by controlling the voltage, the best compromise between image brightness and evenness of image brightness (elimination of hot spots) can be attained.

Dynamic scattering greatly improves resolution due to rapidly and randomly changing the diffuser "grain" pattern. The same effect was demonstrated by replacing the static diffuser with a rotating ground glass plate. This technique works equally as well as the liquid crystal diffuser, but is much more difficult to implement since it requires a relatively large complex mechanical system. The beauty of the liquid crystal is its simplicity. All that is required for its operation is 60 Hz AC, at 40 to 50 volts, connected directly across the LC diffuser. The LC cells have an indefinite lifetime (> 10 years); although rare failures may occur due to shorting of the conductive plates or due to application of a DC voltage.

Two vendors were found that manufacture this type of liquid crystal diffuser. One device did not provide enough scattering to eliminate "hot spots" in the image. The other, from LCD Engineering, Newbury, California, provided more than enough scattering and excellent resolution. A custom LC screen was incorporated into the EAEP viewer. The optimum operating voltage was found to be approximately 45 volts.

3.6 Toroidal Field Mirror

The field mirror is a custom designed and fabricated toroidal mirror. The toroidal surface is preferred due to the mirror imaging off-axis. The mirror forms an image of the relay lenses that lie 31mm off the optical axis in the horizontal plane, and 105mm off axis in the vertical plane. This asymmetry would normally cause the formation of oval shaped exit pupils. Figure 3.6-1 shows a computer generated plot of the exit pupils

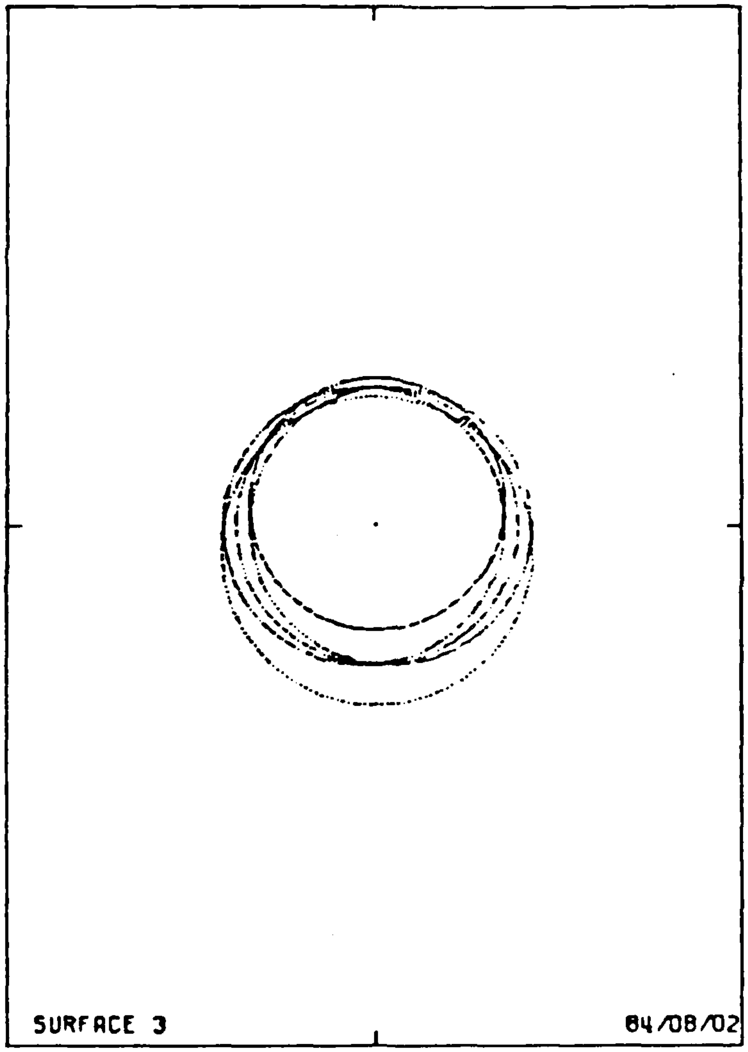


Figure 3.6-1 Exit Pupils Formed by the Four Corners and Center of a Spherical Mirror with Radius = 12 Inches

that would be formed by a 9 inch focal length spherical mirror. The next plot, Figure 3.6-2, shows the rounder and larger exit pupils formed by the toroidal mirror. The mirror is machined out of aluminum, hollowed in the back to reduce weight, and cut to a 9 inch x 9 inch square. The aluminum is then nickel plated and polished to an optical quality surface. The nickel is then overcoated with a layer of aluminum to provide the highly reflective mirror surface. For more than single unit fabrication, the toroidal mirror could be economically fabricated as plastic replication from a negative metal master. The major radius of curvature is 18.370 inches, and the minor radius of curvature is 17.639 inches.

The toroidal field mirror supplied with the prototype HSD-500 is marred by a circular blemish in the left center of the mirror. The blemish was caused by a mounting hole that was drilled too deep and was then plugged with aluminum. Although the plugged hole was noticed early in the mirror's fabrication, it was thought that the blemish caused by the plug would polish-out after the nickel coating was added and polished down. However, the nickel coating did not sufficiently fill the plug marks and remove the blemish.

While viewing imagery, the blemish is hardly noticeable and does not distract from stereo perception. Therefore, rather than spending the time and money to have a new mirror fabricated, the blemished mirror was delivered with the instrument.

During testing of the mirror, it was discovered that the optical ray traces generated during the mirrors design did not accurately represent the viewers optical geometry.

The optical design program that generated Figures 3.3-1 and 3.6-1 did not take into account the offset of the 57mm relay lens in the tangential plane. When this offset is included in the design program, the increased exit pupil size achieved by

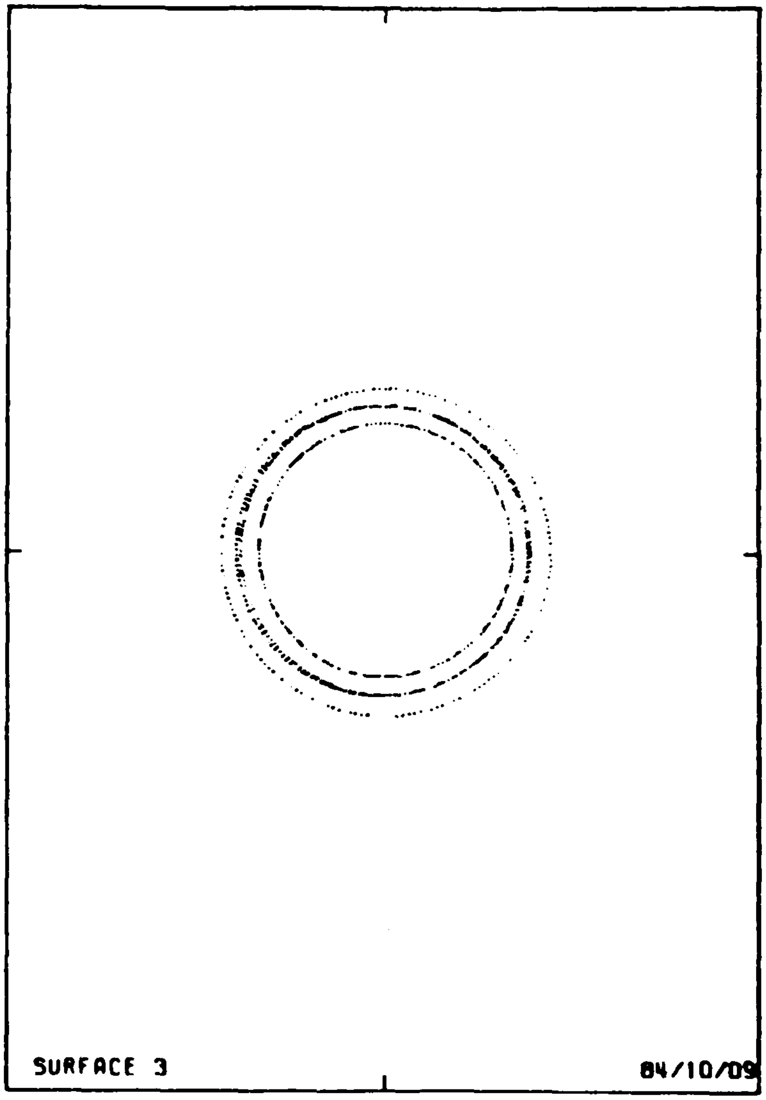


Figure 3.6-2 Exit Pupils Formed by the Four Corners and Center of 9 Inch x 9 Inch Toroidal Mirror

using a toroidal instead of spherical mirror is not significant. In addition, vignetting by the 57mm relay lens (described in the following section), is the limiting factor in exit pupil size, not the shortcomings in the field mirror performance.

Further study is likely to confirm that a field mirror of spherical form will provide only a slight degradation in performance over the more complex toroidal designs and at a significant savings in cost.

3.7 Relay Lens Vignetting

During pre-acceptance testing of the viewer, it was discovered that the exit pupil size was smaller than predicted by the optical ray tracing shown in Figure 3.6-1. Rather than being caused by poor performance of the field mirror, the limiting factor was found to be vignetting by the 57mm Hexanon relay lenses.

Vignetting occurs as the angle between the object (in this case the field mirror) and the optical axis increases. The effect is the same for two axially centered, but longitudinally separated apertures. When observing the apertures from off-axis, one aperture occludes, or vignettes, the other. In the EAEP system the pupils formed by the corners of the field mirror are vignetted, because the field mirror corners 'see' a vignetted aperture of the relay lens. The effects of this situation are illustrated in the Viewing Parallax section of the test results. The vignetting of the 57mm Hexanon lens is severe enough to be the limiting factor in exit pupil size.

The solution to the vignetting problem is to replace the 57mm Hexanon lens with a lens optimized for minimum vignetting. For most optical systems, vignetting is not a crucial factor. Consequently, most commercially available lenses, especially large aperture ones, have significant

vignetting. A commercially available lens with acceptable vignetting performance has not been found. Therefore, a custom optical design will probably be necessary. A custom lens has the advantage of allowing the optimization of those lens performance characteristics that are most important to the particular instrument. In the case of the EAEP system, the parameters to be optimized include a large aperture and freedom from vignetting.

A preliminary study and lens design has been conducted to define a nonvignetting, large aperture, projection lens. A lens was designed to meet the optical requirements of the current prototype specification. The specifications included a 38mm pupil, 7X magnification, a 44mm object size, and no vignetting over the field. This would allow it to replace the 57mm f/1.2 lens that is now being used.

The design that was produced is shown in Figure 3.7-1. The lens has a 36mm pupil on axis, falling to 34mm at the extreme field point. It covers the 44mm object field and enlarges it by 7X to the image. With optimization, the optical parameters can all be made to exactly match the specification.

The physical parameters were not highly constrained in this design effort. Notably, the largest element of the lens is 71mm in diameter. A maximum diameter of 63mm can be allowed in the EAEP viewer. As tradeoffs are made in carrying the design beyond this initial work, the diameter constraint can be applied to the lens.

3.8 Magnification

The magnifying power of the EAEP viewer is not as easily defined as it is for normal eyepieces. This section discusses the definition of magnifying power as it applies to the EAEP viewer.

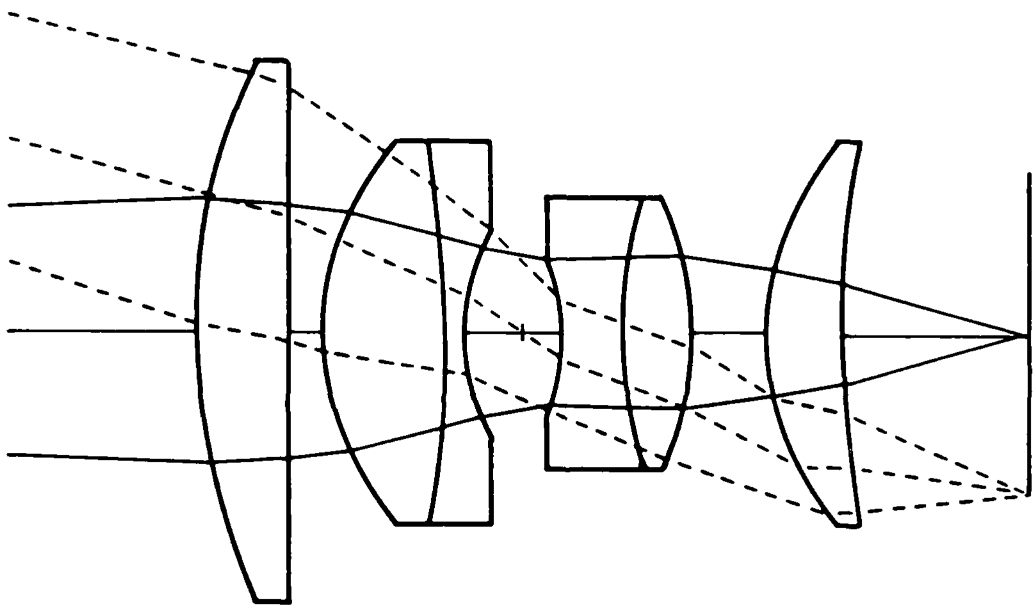


Figure 3.7-1 Full Scale Design Layout for Large Aperture Relay Lens

r normal microscope eyepieces of focal length = f, the magnifying power (MP) is defined by the equation: MP = 10 inches/f. The value in the numerator (10 inches), is the standard viewing distance at which the magnifying power is defined. For a normal eyepiece, the eye perceives the image as if it were fixed at infinity, but the magnifying power is defined as if the object was at 10 inches from the viewer. In the EAEP viewer, a different situation exits. The eye perceives a diffuse image lying in the plane of the field mirror. The size of the image, and thus the magnification, are dependent on the viewer's distance from the field mirror. The EAEP magnification can be calculated by the equation: $MP = MP_{EAEP} * 10$ inches/D, where D is the distance from the eye to the image at the field mirror. The magnification of the real image at the field mirror is equal to the product of the relay lens magnifications: 2.3X * 7X = 16.2X. For the nominal viewing distance of 18 inches, the magnifying power is then 16.2 x 10 inches/ 18 = 9X. The usable longitudinal head movement of the EAEP system is approximately +2 inches and -2 inches resulting in a 16 inch to 20 inch viewing distance. A usable magnification range of 10X to 8X is thus obtained.

3.9 High-Intensity Light Source

The need for using a high-intensity light source in conjunction with the EAEP viewer was illustrated by Figure 2.0-5, showing the light fall off due to the expansion of the exit pupils. The light available to the microscope system is distributed over the exit pupil area. As the exit pupils are expanded, the intensity of the light that enters the eye falls off with the square of the exit pupil radius. Thus, for the 44mm diameter exit pupils, the illumination falls off to 0.5% of the value for normal pupils. Additional light losses occur via back reflections and absorption within the optics, and by the LC diffuser scattering light outside the aperture of the second relay lenses. The light requirement is further increased by the fact that the Zoom-500 microscope has a light throughput of only 1% to 2%.

The original EAEP Contract did not include funding for the high-intensity light source, but funding was provided in a 1985 contract modification.

The light source designed for the EAEP system consists of two high-intensity quartz reflector lamps configured similarly to the original Richards light source. An approach using high-intensity xenon arc lamps and fiber optic bundles was investigated, but was found to be much more costly, complex, and negligibly brighter.

Figure 3.9-1 shows the layout of the high-intensity light source. The tungsten light sources are Sylvania EJL, 200 Watt, 24 volt quartz lamps with integral dichroic reflectors. The lamps are combined with 80mm condenser lenses that focus the light into the entrance pupils of the Zoom-500.

The light sources follow the movement of the Zoom-500 rhomboid arms via a belt-coupled follower mechanism used for the original Richards source. However, the original lamp tracking mechanism did not accurately follow the rhomboid arm movement. The addition of stiffer belts and springs on the tracking mechanism greatly improved its accuracy. The radius of the arc the lamps follow can still be changed in order to accommodate different power objectives. When using normal eyepieces, the high-intensity light sources may, in fact, be very useful for viewing very dense film or when using very high magnification.

When using the normal eyepieces with the high-intensity lamps, extremely high-image brightness could be observed and so the lamp voltage is reduced. Operating at this decreased voltage causes the color temperature of the lamps to decrease. The addition of blue filters to the 10X eyepieces raises the color temperature and further decreases the brightness seen through the eyepieces.

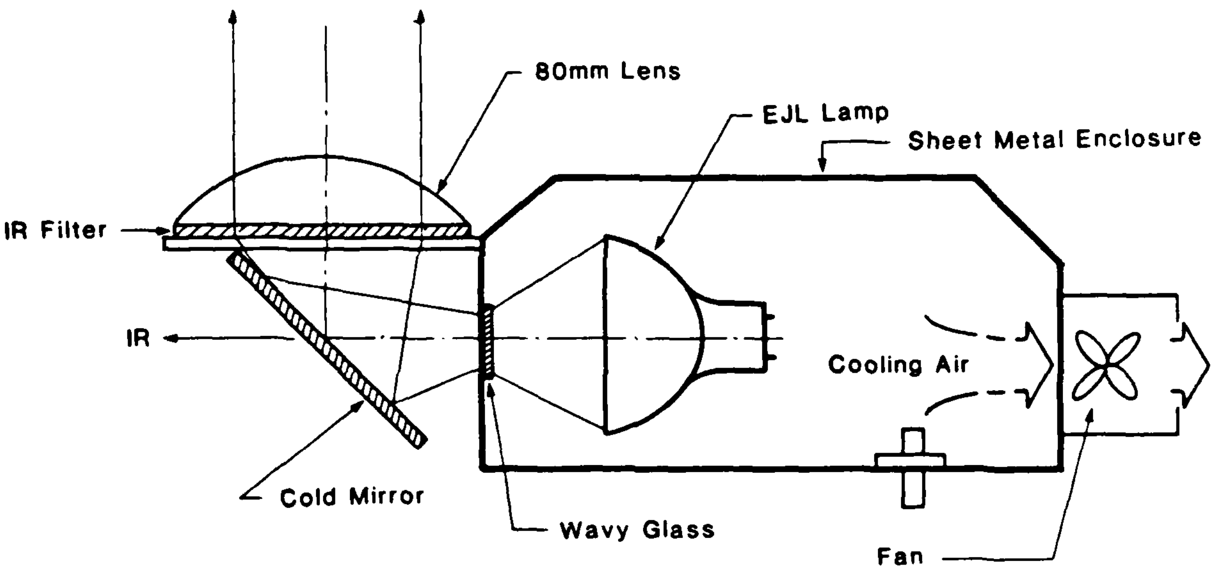


Figure 3.9-1 High-Intensity Light Source

Figure 3.9-1 shows the high intensity light sources incorporated into the Richards light table. To minimize film heating caused by the lamps, a dichroic cold mirror and hot mirror are included. The 45 degree cold mirror allows most of the infrared radiation to pass straight through and reflects the visible light upwards. The 90 degree hot mirror reflects any remaining IR downward, while allowing the visible light to pass. The lamphouse includes a small fan that draws cooling air past the lamp and out the back of the lamp assembly.

A special sheet of ground glass above the lamp assemblies allows large area viewing of the film, while two arc-shaped unground apertures allow the light from the high-intensity lamps to enter the Zoom-500 directly. This nondiffuse illumination is needed to preserve the illuminator efficiency. To help diffuse the high-intensity lamp filament images, a piece of slightly diffusing "wavy glass" is included in the lamp assembly.

The high-intensity light sources are capable of surpassing the brightness requirement of 300 foot-lamberts at all but the highest magnifications. Although the fairly simple design interfaces well with the existing Richards light table, there is room for improvement. The condenser lens in the present design relays an off-axis image of the lamp filament that fails to collect all of the available light energy. Theoretically, a lamp of the same design can produce a brighter image by directing more of the light through the microscope entrance pupil. It may be possible to replace the current lamp assembly design with one that includes an off-axis paraboloidal reflector. This configuration, although more complex, should be more efficient and provide more uniform illumination.

4.0 ELECTRICAL

A few electrical modifications and additions were made to the Richards HFO-500 light table in order to power the high-intensity light sources and the liquid crystal diffuser.

The high-intensity light sources use 24 volt, 200 watt lamps which draw approximately eight amperes. Two 12/24 volt, ten amp transformers (one for each lamp) replace the smaller original transformers. The lamp brightness is controlled by varying the input voltage to the transformers via the triacs within the table. An interlock switch on the viewer switches the lamp voltage from 24 to 12 when the unit is lifted. This feature maintains a safe illumination level when using normal eyepieces.

A smaller transformer has been added to provide operating voltage for the interlock relays and for operation of the LC diffuser. A 0.1 micro farad capacitor filters out any DC voltage that could damage the LC diffuser. A potentiometer controls the voltage across the LC cell, thus controlling the diffusing characteristics.

The lamp cooling fans are operated directly from the 115 volt AC line coming into the light table.

value at 2.7%. This amount of distortion is just detectable when viewing a stationary image. It becomes more noticeable when the image moves during scanning. The EAEP measurement reticle is placed in the real image plane of the Zoom-500 and thus, measurement accuracy is not affected by the distortion mentioned above.

The EAEP viewer was specified to maintain the same geometric orientation as the normal eyepieces. Due to reflections within the viewer, the image becomes rotated 180 degrees as compared to the image viewed through the normal eyepieces. To correct for this reversal, the image rotators on the Zoom-500 should be rotated through 180 degrees. When this is done, the exact geometric orientation between eyepiece and EAEP viewing is preserved. Stereo alignment is not disrupted and no movement of the film chips is required.

6.6 Zoom Magnification

No modifications have been made to the Zoom-500 optical system. Thus, the full zoom range from 0.6X to 3.3X is operational, when using the EAEP viewer, and has been demonstrated.

6.7 Stereomicroscope Modification

With the exception of adding a small mounting post to the Zoom-500 eyepiece assembly, there have been no modifications made to the stereomicroscope itself. The modifications that have been made to the Richards light table are performance upgrades necessary to accommodate the EAEP system mechanical structure and the high-intensity light sources. The modifications in no way limit the performance of the standard Zoom-500/HFO-500 combination. The modifications include:

- Adding springs to the vertical focusing slide in order to handle the increased weight of the EAEP system.

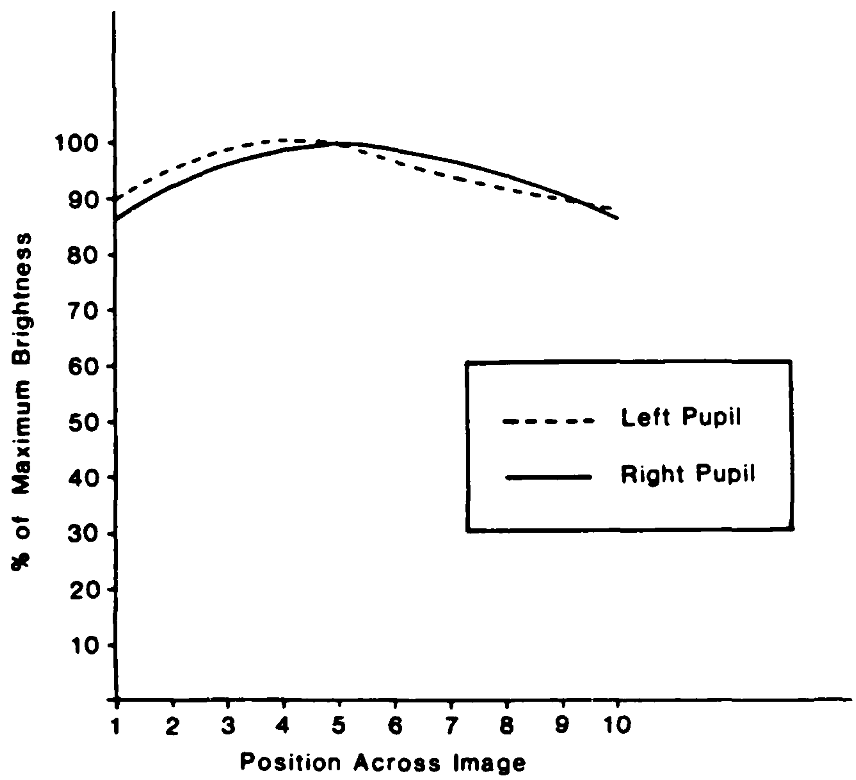


Figure 6.5-2 HSD-500 Illumination Uniformity

results of this test, showing brightness as a function of position across the image, are presented in Figure 6.5-2. The illumination uniformity is dependent on the alignment of the condenser lens to the lamp filament and the position of the lamp assembly with respect to the stereomicroscope rhomboid arm. Variability in the lamp construction may occasionally require that repositioning of the condenser lens be performed, although tests with a group of ten Sylvania EJL lamps indicated that their construction was very uniform. It is also important that the lamp assembly be accurately aligned to the rhomboid arms. The Richards light source tracking mechanism is not designed to provide the tracking accuracy required by the EIKONIX high-intensity lamps. Therefore, despite modifications made to improve the tracking mechanism, the lamphouses may also require periodic alignment.

The LC diffuser scatters light quite evenly across the entrance pupil of the 57mm Hexanon relay lens. However, all diffusers show a brighter peak in the direction of the incident light beam. In this case, the brighter peak in the direction of the image forming beam fills the center of the entrance pupil of the 57mm lens more brightly than the edges, resulting in the center of the exit pupils being brighter than the edges. Thus, a single image point will not maintain exactly the same brightness when viewed from different positions within the exit pupil.

A convenient way to measure image distortion is to place a straight edge in the Zoom-500 image plane and a straight-edge at a conjugate position at the field mirror. At the outer edges of the mirror, the distance between the image of the straight edge and the real straight edge, divided by the mirror radius, is equal to the total distortion at that point. Since the distortion in the EAEP system is not radially symmetric, the distortion was measured in this way for all four edges. The distortion in the horizontal direction was found to be 5.4%. The distortion in the vertical direction was found to be half this

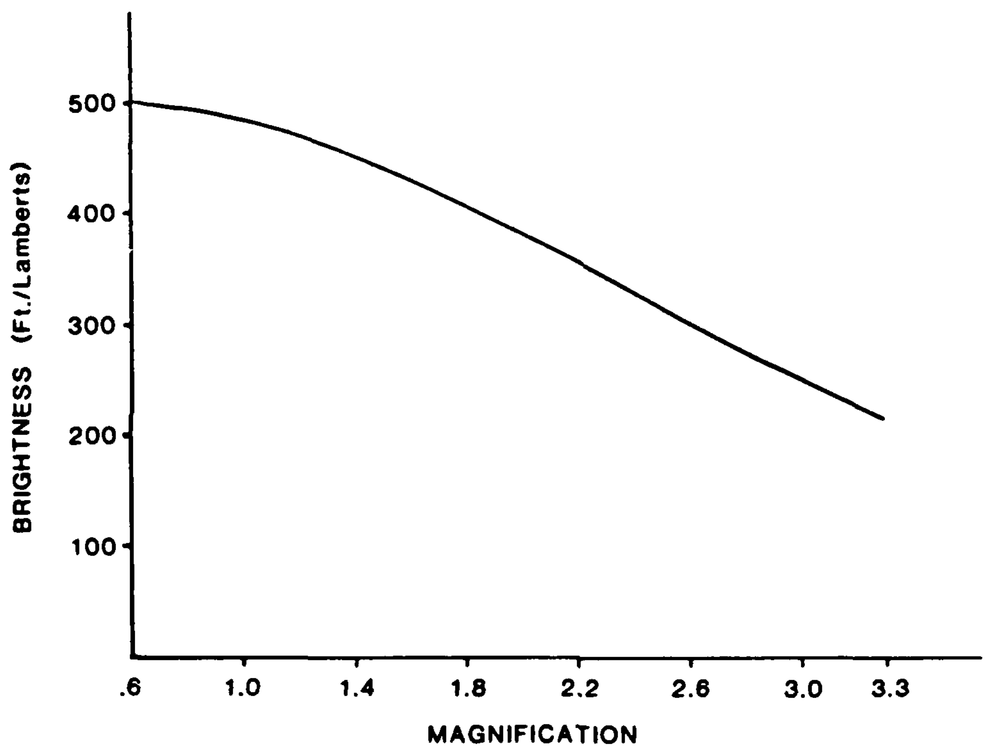


Figure 6.5-1 HSD-500 Brightness as a Function of Magnification

can only demonstrate subjectively. Those that can only be demonstrated include stability, absence of discernible flicker, geometric orientation, and absence of defects that distract from comfortable viewing. EIKONIX believes that viewing the EAEP image has confirmed that the goals for these parameters have been satisfactorily met.

Those parameters that have been quantitatively tested include the illumination uniformity, image brightness, and image distortion.

The overall image brightness was measured using an EG&G photometer configured to measure luminance in foot-lamberts. In addition to the normal photometer head, a 5mm aperture stop was added to the lens assembly to simulate the iris of the viewer's eye. The conversion factor between using the photometer head with an aperture, to using the photometer head without an aperture is 200X. The brightness measurements for open gate illuminance, as a function of magnification, are plotted in Figure 6.5-1. Note that the specified performance for open gate brightness of 300 foot-lamberts was achieved for magnifications of less than 2.6X.

The specification for illumination uniformity across the image plane allows a tolerance of 10%. The performance is measured as illumination across the image plane as viewed from a fixed position within the exit pupil. Although there was no specific requirement on the brightness for a single image point versus position across the exit pupil, visually this performance parameter varies little within the full pupil area of Figure 6.2-1.

The uniformity of illumination across the image plane was measured using the same EG&G photometer. The lens used for measuring luminance covers an eight degree field and was thus used to scan across the EAEP image giving illuminance (in foot-lamberts) as a function of position across the image. The

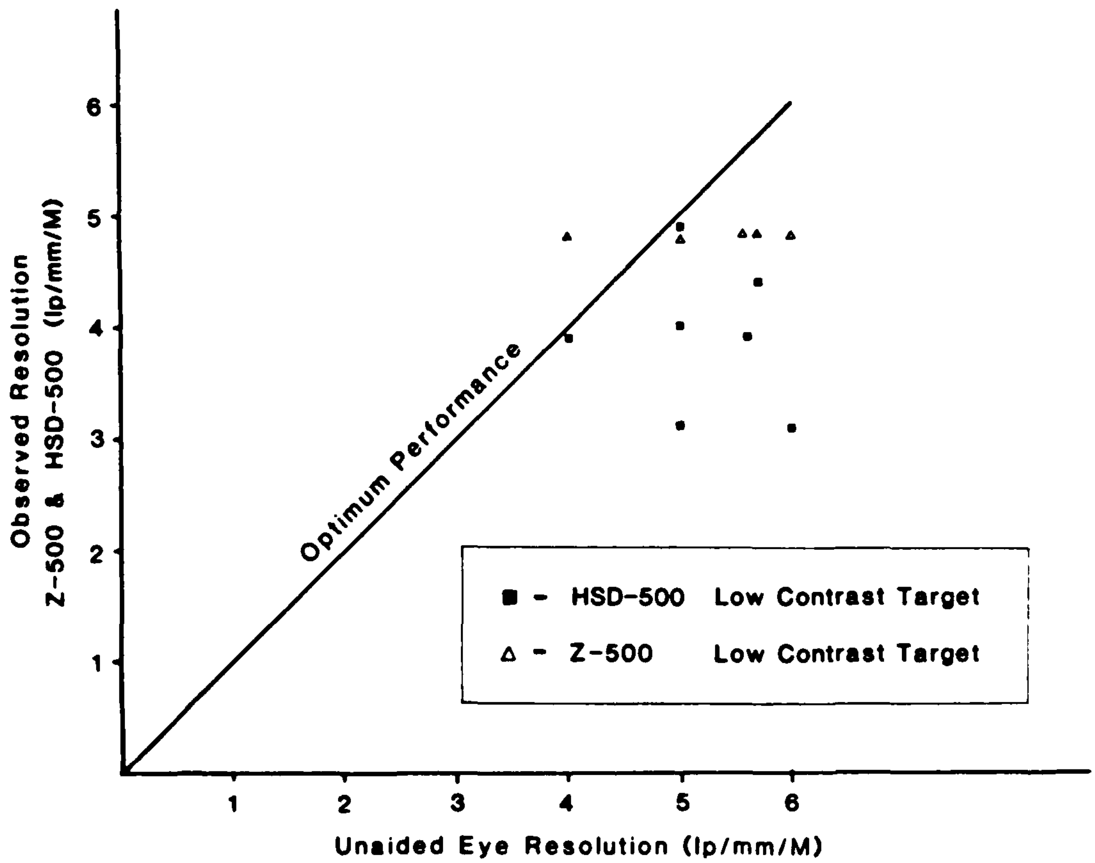


Figure 6.3-2 Instrument Resolution Performance Correlated by Observer to Unaided Eye Resolution Performance for Low-Contrast Target

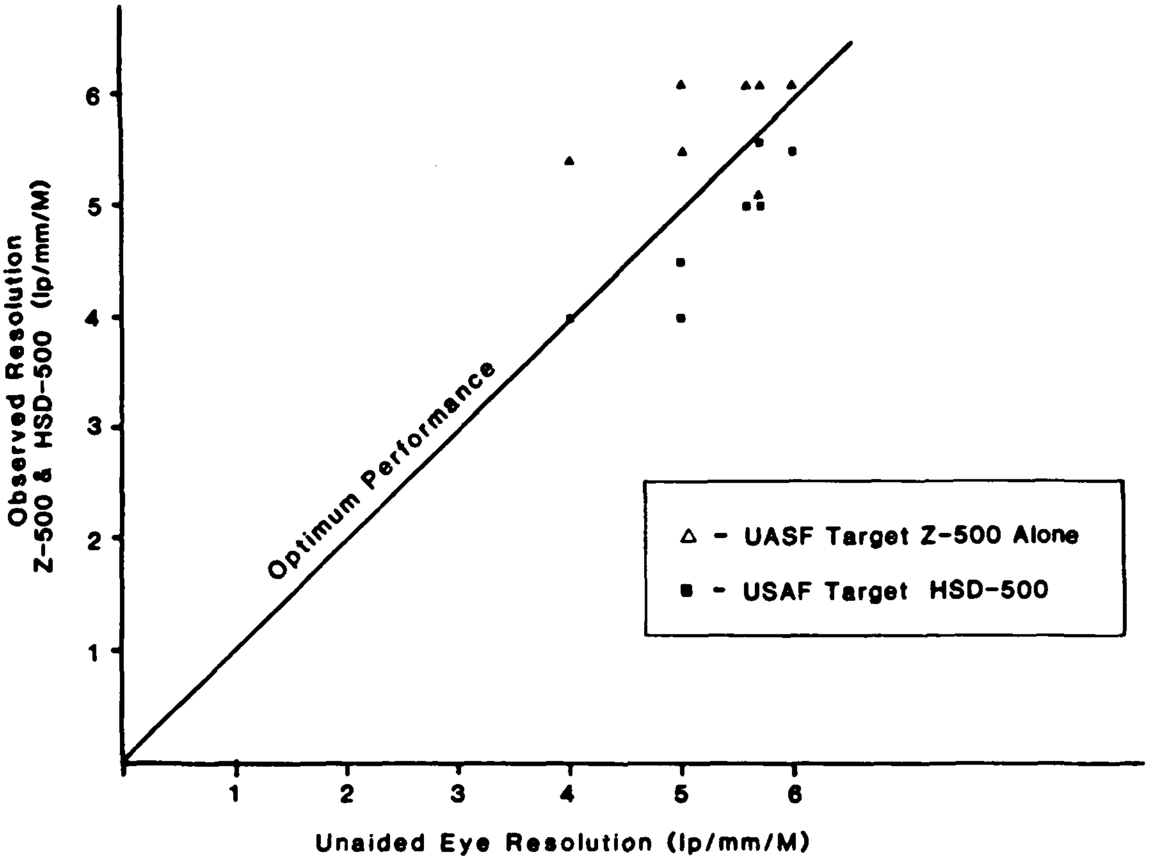


Figure 6.3-1 Instrument Resolution Performance Correlated by Observer to Unaided Eye Resolution Performance for High-Contrast USAF Target

system resolution data (using the same target and dividing by the EAEP system magnification), any deviation from a 1:1 linear relationship can be attributed to the degradation by the EAEP system; including the Zoom-500. The test has been performed under best case and worst case conditions. Best-case conditions utilized a high-contrast (100:1) USAF test target (clear lines on a dark background), and worst case, a low contrast (2:1) 15 bar target with dark lines on a light background. Resolution tests were performed with the Bausch & Lomb Zoom-500 in mono mode and at highest magnification, i.e., 3.3X the magnification of greatest interest for high-resolution viewing.

To distinguish the performance of the Zoom-500 from that of the EAEP system, the resolution tests were also performed using the stereomicroscope and the normal 10X eyepieces. The results of these tests are presented in Figures 6.3-1 and 6.3-2. Figure 6.3-1 shows the results of viewing the USAF target with both the EAEP system and with the normal eyepieces. The EAEP system scored an average resolution of 4.7 lp/mm/M, while the Zoom-500 with eyepieces average resolution was 5.8 lp/mm/M. Figure 6.3-2 is a similar plot for the low contrast target. The average EAEP system resolution was 3.8 lp/mm/M and the Zoom-500 was 4.8 lp/mm/M. Thus, for both the best and worst cases the EAEP system has surpassed the minimum resolution goal of 3 lp/mm/M.

6.4 Viewing Format

The field mirror that forms the viewing area of the EAEP system is round and has a diameter of 9 inches. The specification requires a minimum field mirror diameter of 8.5 inches.

6.5 Image Quality

The assessment of image quality involves some parameters which are subject to direct measurement and others that

The most vignetting occurs at the corners of the image, as illustrated in Figure 6.2-1.

Each corner of the field mirror sees a differently shaped vignetted aperture of the 57mm relay lens. These become exit pupils of various shapes which focus at slightly different distances from the field mirror. For this reason, perfectly round focused exit pupils are not formed. The pupil diagram in Figure 6.2-1 shows the various shapes of the vignetted exit pupils formed at the best focus. Note that the shaded central portion is the only area that receives light from the entire field mirror. Thus, this area will be brighter than the surrounding partial exit pupil.

6.3 Resolution

Resolution measurements are used to determine the ability of an optical system to preserve fine spatial detail in the object. The resolution requirement is 3 lp/mm/M (3 line pairs per millimeter per unit magnification) and a goal of 5 lp/mm/M has been set. Resolution is not a straightforward measurement in that it involves a subjective measurement by human test-target readers. First, there is a judgment by the test target reader as to what a resolved and nonresolved target looks like. Second, since the EAEP system presents an image to the viewer that is fixed at 18 inches away, correction for the viewer's eyesight at this distance must be included. Otherwise, the viewer's eyes may limit the resolution, not the EAEP system. Because of these difficulties, the following test method has been devised to minimize the operator eyesight factor and to test the EAEP system under a variety of conditions.

Viewer eyesight and their criteria for resolution can be partially corrected for by testing their eyesight with a standard USAF test target at an 18 inch viewing distance. If this unaided-eye resolution data is plotted against the EAEP

HSD-500 Exit Pupil Overlap

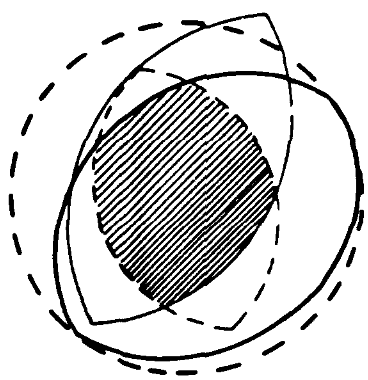


Figure 6.2-1 Exit Pupil Outlines from the Four Corners of the Toroidal Mirror

Two methods were used to measure the parallax. The first involved measuring the exit pupils themselves. The outlines of the pupils formed by the four outer corners of the field mirror were individually traced by masking off all but the desired corner and observing the pupil formed by it. A copy of these traces are shown in Figure 6.2-1. The area in which the four pupils overlap, indicated by the shaded section, is the area of the full exit pupil. When the operator's eye is placed within this area, he can see the four corners and thus, the entire image (the corners are the first part of the image to disappear). This method of measuring maximum head parallax yielded results of ±0.45 inches.

A second method used a mock eyeball affixed to a translating stage to determine the range over which the image could be observed. This approach eliminates the inaccuracy associated with human head position measurement. The mock eye consists of a lens, iris, and ground glass "retina" that correspond to the dimensions of the human eye. By moving the mock eye across the pupil, and observing where the full image is visible on the ground glass, the width of the exit pupil can be determined. The results of the mock eye method of measurement indicate a maximum horizontal parallax of ±0.5 inches; about 0.05 inches greater than the exit pupil trace measurement method.

The head moving parallax of ±0.5 inches falls short of the specified ±0.75 inches. The reduced parallax was determined to be caused by vignetting in the 57mm Hexanon relay lenses. It is the pupil of these lenses that, when projected by the field mirror, become the exit pupils of the system. When used on axis, these lenses have a pupil diameter of 44mm. When used to image at the corner of the field, corresponding to the corner of the field mirror, these pupils become vignetted. The resulting pupil shape for off-axis image points become oval with a width less than 44mm. As discussed above, the system exit pupil is the composite of the pupils formed from each point in the image.

Table 1

Requirements

Sect.#	Requirement	Test	Demonstrate	Analysis
6.1	Viewing Distance		X	
6.2	Head Moving Parallax	X		
6.3	Resolution	X		
6.4	Viewing Format			X
6.5	Image Quality	X	X	
6.6	Zoom Magnification		X	
6.7	Stereomicroscope Modification			X
6.8	Interface		X	
6.9	Human Factors Engineering		X	X
6.10	Operating Conditions	X		
6.11	Reliability and Maintainability			X
6.12	Standard Parts			X
6.13	Electrical Requirements		X	X
6.14	Treatment and Painting		X	X
6.15	Safety and Operational Protection		X	X

6.0 TEST RESULTS

A prototype EAEP viewer, fitted to the Bausch & Lomb Zoom-500 stereomicroscope and Richards HFO-500 light table, has been delivered to ETL for testing and evaluation. The main goal of the EAEP viewer is to reduce operator fatigue normally associated with long periods of binocular viewing. Ultimately, its usefulness and success at reducing operator fatigue can only be determined during actual use of the instrument. Tests concerning the instrument's construction and performance have been conducted at EIKONIX by EIKONIX personnel.

Table 1 lists the specific performance evaluations performed on the instrument. These have been divided into three evaluation categories: quantitative tests, descriptions of the demonstrations performed, and analyses of the viewer's design. At the end of this section, Table 2 presents a brief summary of the test results.

The following sections describe the results of the performance verification tests.

6.1 Viewing Distance

The distance from the operator's eyes to the image was specified to be between 10 inches and 18 inches. The opto-mechanical geometry has been designed and shown to provide a nominal viewing distance equal to 18 inches. Additionally, a physical relief of four inches from the operator's eye to the bezel of the viewer has been demonstrated.

6.2 Head Moving Parallax

The head moving parallax is the distance an operator (with an average eye interpupillary spacing of 63mm) can move his head and still retain full field stereo viewing. The specification for head moving parallax is 38mm (±0.75 inches).

5.0 MECHANICAL DESIGN

Three mechanical assemblies comprise the EAEP viewer; the fixed mounting plate and mirror support, the main optics assembly that swings out of the way, and the field lens reticle assembly that attaches to the Zoom-500 eyepiece tubes.

The mounting plate attaches the EAEP viewer and the Zoom-500 to the focusing slide of the light table and also supports the field mirror mount and the main optics assembly. The optics are supported by a sturdy aluminum framework which is covered by a painted sheet metal enclosure. Hinges on the optics assembly allow it to swing upwards approximately 180 degrees. Pneumatic pistons on each side of the instrument minimize the force necessary to raise the optics assembly. In addition, the pistons restrict the assembly from falling rapidly downwards and injuring either the operator or equipment.

The field lens/reticle assembly slides into the eyepiece tubes of the Zoom-500. It contains the field lenses and reticle that lie at the internal stereomicroscope image location. There are three removable tubes; two contain field lenses, and one contains a field lens and reticle. Thus, the reticle can be placed in the right channel, left channel, or not installed at all. This assembly also contains the reticle rotator/readout knob that turns the reticle tube via a gear mechanism.

The increased weight of the EAEP viewer necessitated the addition of support springs. The springs reduce the weight supported by the focusing mechanism and make focusing smoother and easier. Larger knobs on the fine focusing mechanism have also been added to allow easy operator access.

- Using stiffer belts and springs on the light source tracking mechanism to improve the tracking accuracy.
- The addition of large knobs on the fine focusing adjustment allowing easier operator access.
- Electrical modifications for the high-intensity light source including larger transformers, a low voltage interlock, and a small transformer to power the liquid crystal diffuser.
- Adding blue filters to the Bausch & Lomb 10X eyepieces to raise the color temperature and lower the brightness of the image through the eyepieces.

6.8 Interface

The ease of alternating between normal stereo and EAEP viewing can be easily demonstrated. A group of eight untrained operators changed between EAEP and non-EAEP viewing; and back again. The time for switching from or to heads-up viewing were about equal and took the average operator 60 seconds. The times ranged from 30 seconds to 90 seconds.

6.9 Human Factors Engineering

It is apparent to an operator using the EAEP system that it incorporates good ergonomic design practice. All of the normal Zoom-500 controls are within easy reach of the operator while comfortably seated viewing the EAEP system image. A pneumatically adjustable chair has been provided to accommodate the small height change between EAEP and non-EAEP viewing.

The viewer geometry provides a viewing angle of 1.5 degrees downwards. This is within the suggested viewing angle of 0 (horizontal) to 45 degrees downwards as specified by the Design Handbook for Image Interpretation Equipment, page 6.1-7. The viewing angle was chosen to keep the operator

close to the stereomicroscope and light table controls, thus providing a comfortable position for image analysis. A steeper viewing angle would require an elevated operator seating arrangement; an awkward position from which to reach the stereomicroscope and light table controls.

6.10 Operating Conditions

There are no components within the instrument that are temperature or humidity sensitive within the limits of a normal indoor work environment.

Due to the low thermal capacity of the film, a direct measurement of the film temperature is difficult to obtain. However, the following method was used to get at least a comparative measure of film temperature. A thermistor probe was placed in contact with a piece of 8 inch x 10 inch Plus-X film (Estar thick base) with a density of 1.05. The temperature of the film was measured over a period of 30 minutes as the film was illuminated by the high-intensity lamps at full power. The film temperature, as a function of time, is presented in Figure 6.10-1. The maximum recommended temperature for use of this film is 200° F.

In addition to the temperature test, another 8 inch x 10 inch piece of Plus-X film with an average density of 1.34 (95% of the incident radiation is absorbed or scattered), was illuminated at full intensity for a period of 30 minutes. No physical damage to the film, such as buckling, discoloration, etc., was observed.

6.11 Reliability and Maintainability

The instrument's opto-mechanical design is inherently very reliable; incorporating no moving parts subject to excessive wear. The liquid crystal diffuser is anticipated to have an

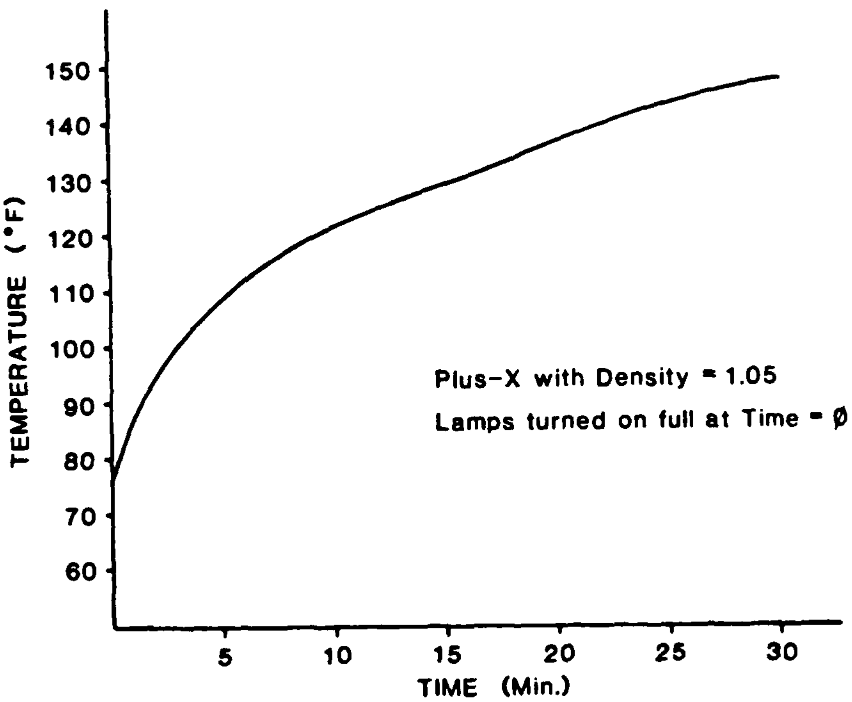


Figure 6.10-1 Film Temperature as a Function of Time

almost indefinite lifetime, although good statistical data is not available. The liquid crystal diffuser under evaluation at EIKONIX has shown no degradation under normal use.

Maintenance involves only periodic cleaning of the optical components and lamp replacement. All optical surfaces can be easily reached by removing the sheet metal enclosure. The lamps are easily accessible via hinged doors on the bottom of the Richards table.

6.12 Standard Parts

The EAEP system, HSD-500, is a custom prototype mechanical construction. However, full use of standard USS fasteners and fittings has been made.

Where possible, the optical components are standard items obtained from large stock-item optical houses. The notable exceptions include the field mirror and the large aperture relay lenses.

6.13 Electrical Requirements

All electrical power is obtained from the Richards light table electrical system which requires a single 110 volt AC, 50/60 Hz and 15 ampere input.

6.14 Treatment and Painting

The paint on the outer shell of the instrument has been matched to the color of the Richards light table. All other surfaces have been anodized or painted flat black, consistent with good optical design.

6.15 Safety and Operational Protection

Two areas of concern for operator safety are protection from viewing the high-intensity light source through the normal 10X eyepieces and prevention of head impact when raising or lowering the EAEP system. The first concern has been addressed by providing a low voltage interlock on the EAEP system. When the system is lifted out of the way to allow normal eyepiece viewing, the interlock switches the lamps from 24 to 12 volts, thus greatly decreasing the light intensity.

Two air pistons, one on each side of the viewer, prevent the instrument from falling down from the raised position and possibly hitting the operator. The pistons provide a slow smooth transition from the raised to lowered position and vice versa.

Table 2

HSD-500 TEST RESULTS SUMMARY

Sect.#	REQUIREMENT		
6.1	Viewing Distance	Demonstrated Distance	
6.2	Head Moving Parallax	Measured Parallax	±0.5
6.3	Resolution	USAF Resolution Low Contrast	5.0 lp/mm/M 3.9 lp/mm/M
6.4	Viewing Format	Analyzed	
6.5	Image Quality	Freedom from Defects Brightness @ 0.6X Brightness @ 3.3X Brightness Uniformity Horizontal Distortion Vertical Distortion	 500 ft. lum. 220 ft. lum. 13% 5.4% 2.7%
6.6	Zoom Magnification	Full Range Demonstrated	
6.7	Stereoscope Modification	Analyzed	
6.8	Interface	Ave. HSD Setup Time Ave. HSD Take-Down Time	60 seconds 60 seconds
6.9	Human Factors	Demonstrated	
6.10	Operating Conditions	Film Temp. after 30 min. Film Damage	148° F None
6.11	Reliability and Maintainability	Analyzed	
6.12	Standard Parts	Analyzed	
6.13	Electrical Requirements	110 Volt Operation	
6.14	Treatment and Painting	Demonstrated	
6.15	Safety and Operational Protection	Features Demonstrated	

7.0 PRODUCTION COST

Using the EAEP viewer as a baseline, system costs have been estimated to produce multiple units. These costs include manufacture of the HSD viewer, upgrade of the Customer furnished Bausch & Lomb Zoom-500 and Richards HFO-500 light table, assembly and test of the complete system, and shipment to the Customer.

These estimated costs are accurate with respect to the current system. It is anticipated that before production of these units, a second preproduction prototype would be made. During this effort, time would be allocated to perform the design modifications discussed in this report. Specifically, the areas to consider are field mirror design, light source design, large pupil lens design, and production engineering. It is estimated that the second prototype would require approximately a one man-year of effort in engineering, fabrication, and testing.

The production costs given are estimates and could be influenced by the results of the second prototype effort if it were funded. Larger quantities could allow more significant price savings depending on design modifications for mass production that could be implemented.

Table 3

Estimated Production Cost

	Number of Units		
	1	**5**	**25**
Unit Cost	43K	36K	24K

The production cost goal of $ 15,000 per viewer was not met. However, the maximum production cost of $ 25,000 for quantities of 25 units, was not exceeded. Furthermore, the original cost goals were set for production of the viewer alone, while the costs quoted above include the viewer, the high-intensity light source, and modifications to the light table.

8.0 SUMMARY

An Extended Area Exit Pupil Viewer, designated the EIKONIX Heads-Up Stereo Display (HSD-500), has been designed and fabricated. It provides greatly relaxed viewing of stereo film pairs. The instrument met all the design goals with the exception of the exit pupil size, which is smaller than predicted, and the image brightness, which falls below 300 foot-lamberts at the uppermost magnification. These shortcomings do not significantly impact the performance of the instrument which provides a good demonstration of the patented EIKONIX pupil expansion principle.

The HSD-500 provides a flicker free image with a resolving power of 4.7 lp/mm/M. The image is easy to view, allowing up to ±0.5 inches of lateral head movement, and provides excellent stereo perception. When desired, switching to normal 10X eyepiece viewing is easily accomplished.

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